

WORLD METEOROLOGICAL ORGANIZATION

WMO TROPICAL METEOROLOGY RESEARCH PROGRAMME (TMRP) COMMISSION FOR ATMOSPHERIC SCIENCES (CAS)

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**PROCEEDINGS OF THE FOURTH
WMO/ICSU INTERNATIONAL WORKSHOP
ON TROPICAL CYCLONES (IWTC-IV)**

(HAIKOU, HAINAN, CHINA)

(21-30 APRIL 1998)



WMO /TD No. 961

(Geneva, Switzerland, 1999)

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**Secretariat of the World Meteorological Organization
Geneva, Switzerland
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APPENDICES

FOREWORD

The World Meteorological Organization attaches great importance to activities relating to tropical cyclones and particularly to the application of research results by Members to improve operational activities such as the forecast and warning of the occurrences and movements of tropical cyclones and the mitigation of damage caused by them.

Following the decisions of the Twelfth World Meteorological Congress (1995) and the subsequent sessions of the Executive Council, and at the kind invitation of China, the fourth WMO/International Council of Scientific Unions (ICSU) International Workshop on Tropical Cyclones (IWTC-IV) was organized with the co-sponsorship of the Australian Aid Agency (AUSAID), the European Community Aid Project to the South Pacific, the United States Office of Foreign Disaster Assistance (OFDA) and the United States Office of Naval Research (ONR).

The primary objectives of the workshop were (a) to review and examine progress made in tropical cyclone research and operational practices since IWTC-III and (b) to identify priorities for the future research and operational activities.

The programme of the workshop was developed by an International Committee chaired by Mr Gary Foley (Australia). The workshop, which brought together active tropical cyclone researchers and operational experts (forecasters and warning specialists) contributed to the United Nations International Decade for Natural Disaster Reduction (IDNDR) as one of the major activities under the demonstration project of Tropical Cyclone Disasters.

Active and fruitful discussions between tropical cyclone researchers and forecasters/warning specialists at the workshop resulted in a number of useful recommendations concerning research, forecasting and warning of tropical cyclones. One of these was that the WMO publication "Global Guide to Tropical Cyclone Forecasting" should be updated and placed on the World Wide Web for easy access by Members. For Members who do not yet have access to the Web, it was decided to produce a version of the Guide on CD-ROM as well as limited hard copy form to ensure all concerned have access to the Guide.

I wish to take this opportunity to thank sincerely the members of the International and Local Organizing Committees, the topic session chairpersons, the Rapporteurs, the participants of the workshop and those who assisted in the preparation of this publication for their valuable collaboration.

Finally, I would like to express my appreciation to the Governments of Australia, Canada, China, France, Japan and the United States of America for providing supplementary support which enabled additional participants to attend the workshop.

(G.O.P. Obasi)
Secretary-General

(i)

CHAPTER 1

1. INTRODUCTION

1.1 Organization and Historical Background

Following the directive of the Ninth World Meteorological Congress (1983), the International Workshop on Tropical Cyclones (IWTC), now referred to as IWTC-I, was organized in Bangkok, Thailand from 25 November to 5 December 1985 under the International Programme Committee (IPC) chaired by W. M. Gray (USA). The workshop was intended to review the current state of knowledge on tropical cyclones and to survey the status of forecasting practices around the globe. The report (with recommendations) was published as the Proceedings of the WMO International Workshop on Tropical Cyclones (TMRP Report Series No. 21). Another outcome of the workshop was the production of a text book, *A Global View of Tropical Cyclones* (GVTC), with R. L. Elsberry as editor and chapter contributions from R. L. Elsberry, W. M. Frank, G. J. Holland, J. D. Jarrell, and R. L. Southern. The enormous success of IWTC-I ensured the continuation of the initiative and IWTC-II was organized to take place in Manila, Philippines in 1989.

This workshop was organized under a newly established IPC, chaired by G. J. Holland with its main objective to determine implementations that could be made to improve forecast office procedures and reduce forecast errors. The report on IWTC-II published as proceedings (TMRP Report Series No. 37) contained recommendations, some of which were a follow up to IWTC-I. However new aspects emerged including a statement on the potential impact of climate change on tropical cyclones, a request for action in installing PC-based workstations in tropical cyclone forecasting offices, and a statement on the International Decade of Natural Disaster Reduction (IDNDR). It was also determined to establish an International Committee for IWTC and provide it with terms of reference. This was achieved through discussion during the tenth session of the Commission for Atmospheric Sciences (CAS-X) and TCP regional body meetings.

The major outcome of IWTC-II was the edition of the *Global Guide to Tropical Cyclone Forecasting*. Edited by G. Holland and with chapter contributions by C. Neumann, R. Merrill, G. Holland, C. Jelesnianski, W. Gray, G. Foley, R. Southern and K. Puri, the guide was published in time for IWTC-III.

Activities relating to tropical cyclone research are included as one of the major components in the implementation of the WMO Tropical Meteorology Research Programme (TMRP). The Eleventh World Meteorological Congress (1991) requested that the Commission for Atmospheric Sciences, through its Group of Rapporteurs on Tropical Meteorology Research (GRTMR) provide scientific advice and guidance on the development and implementation of relevant TMRP projects aimed at helping Members in the tropics improve their forecasting services, and thereby benefit their disaster reduction and economies in collaboration with the WMO Tropical Cyclone Programme (TCP). The Executive Council at its forty-third session (EC-XLIII) in 1992 emphasized the important research aspect of the WMO involvement in the IDNDR in close coordination with ICSU for the demonstration project "Tropical Cyclone Disasters" which was adopted at the first session of Scientific and Technical Committee for IDNDR held in Bonn, Germany in March 1991.

IWTC-III was held in Huatulco, Mexico in 1993. Its specific tasks were to update the text book *Global View of Tropical Cyclones*, which would include a chapter on oceanographic effects; develop a statement concerning Global Climate Change and Tropical Cyclones; and to review progress in tropical cyclone activities since IWTC-II. All of these were achieved. Following review and discussion of the proposed book, *Global Perspectives of Tropical Cyclones* (WMO/TD-No. 693) was published in 1995; edited by R. Elsberry and containing chapters by G. Foley, H. Willoughby, R. Elsberry, J. McBride, and I. Ginis. The contribution of new ideas from

representatives of ICSU can be gauged by the inclusion of a new chapter on oceanographic effects. Sir James Lighthill of ICSU also facilitated the debate and report preparation on tropical cyclone activity with respect to possible climate change scenarios. This multi-authored report was subsequently published in the Bulletin of the American Meteorological Society. A subsequent report was commissioned by CAS to provide a post-IPCC assessment of tropical cyclone climate change under a committee chaired by Ann Henderson Sellers. This report was presented to CAS-XII and published in the Bulletin of the American Meteorological Society

1.2 International Committee (IC)

The IC for IWTC-IV was established on 1 November 1995. It consisted of:

| | | |
|-----------------------|-------------|-------------------------------------|
| - Mr G. Foley | Australia | Chairman |
| - Prof. L. Chen | China | Co-chairman |
| - Dr G. Holland | Australia | Chairman GRTMR |
| - Prof. R. Elsberry | USA | CAS Rapporteur on Tropical Cyclones |
| - Sir James Lighthill | U. K. | ICSU representative |
| - Mr S. Ready | New Zealand | |
| - Mr A. V. R. K. Rao | India | |
| - Mr J. Jarrell | USA | Former Chairman |
| - Mr R. R. Vaghee | Mauritius | |

Subsequently Mr Rao from India retired and his place was taken by Mr S. R. Kalsi just prior to the start of the workshop. The IC was responsible for the overall organization of IWTC-IV including the choice of topics, selection of topic chairmen, rapporteurs and working group members, pre-workshop preparation and production of the topic rapporteur reports, conducting the workshop, preparing the proceedings and arranging additional funding for workshop delegates.

1.3 Objectives of IWTC-IV

Like the previous international workshops, the overall objective was to provide a forum for discussion between researchers and forecasters on the current status of tropical cyclone knowledge and on priorities and opportunities, particularly:

- To review progress made in tropical cyclone research and operational practices since the previous IWTC;
- To identify any roadblocks that are inhibiting progress in a particular area of endeavour;
- To identify opportunities that may prove fruitful to explore or develop; and,
- To set in motion the process of revising the WMO publication, Global Guide to Tropical Cyclone Forecasting.

1.4 Workshop organization

For the purpose of discussion, five major topics were selected for the workshop. These were:

- Topic 1 - Tropical cyclone landfalling processes
- Topic 2 - Tropical cyclone intensity and structure
- Topic 3 - Tropical cyclone motion
- Topic 4 - Tropical cyclone prediction
- Topic 5 - Tropical cyclone impacts

The topic chairmen responsible for the production of the workshop report facilitated discussion during the morning plenary sessions, and were assisted by their rapporteurs in presenting information to the group. The list of topic chairmen and rapporteurs is given in Appendix B. In the afternoon session participants were divided into 7 smaller discussion groups, with nominated chairmen and rapporteurs. A record of the main points and recommendations that emerged from these meetings was then given to a group of workshop rapporteurs who condensed and synthesized the information, presenting this at the final plenary topic discussion sessions held in the second week of the workshop. The list of workshop rapporteurs who contributed to the final topic discussions and to this report is given in Appendix C.

Apart from these major topic discussions, the degree of interaction between participants was maximized by setting up the opportunity for additional special focus groups to meet and discuss specific topics. Meetings were held in the evening of the first week and in the afternoon and evening of the second week and were enthusiastically attended by participants. These included talks on (with chief facilitator indicated): Air-Sea Interaction Effects (J. Lighthill), Autonomous Aerosonde (G. Holland), Parametric Wind Field Modelling (B. Harper), Extratropical Transition (J. Abraham), Economic Impacts (R. Pielke), Recent GPS sonde observations of tropical cyclones (P. Black), Studies on Polygonal Eyewalls (M. Montgomery), Wind destruction scale for the tropics (C. Guard) and Satellite Observing Systems (R. Zehr).

A forecasters' meeting was held on Wednesday 29 April where forecasters highlighted their perspectives on operational and research needs. The report of that meeting appears as Appendix A.

Dr G. Holland also facilitated a meeting on the proposed upgrade of the Global Guide to Tropical Cyclone Forecasting on Tuesday 28 April, where lead authors and content of the document were discussed. The outcomes of that meeting were reported to the plenary session on the next morning and a final plan and production timetable was set in place.

1.5 Preparation of the final report

The five topics' final reports and the recommendations emerging from the workshop were written by the nominated participants shown in Appendix C. The editorial committee comprised G. Holland, G. Foley and I. Shepherd.

CHAPTER 2

2. SUMMARY AND RECOMMENDATIONS

2.1 The Classification of all the Recommendations is as follows:

- General recommendations
- Recommendations for WMO
- Research and applied research recommendations
- Forecasting recommendations

2.2 General Recommendations

Major General Recommendation

2.2.1 The future of the Global Guide to Tropical Cyclone Forecasting was discussed at a special meeting and in plenary. **The guide was seen as a valuable forecast reference and it was recommended that it undergoes an evolutionary revision and be reissued.** Several specific aspects were addressed:

- The revised Guide should be published primarily as a Web version, with limited Hard Copy and a CD ROM version.
- Subject to volunteer translators being available, Chinese, French and Spanish versions should be provided on the Web.

The structure of the Guide was revised slightly with some name changes, amalgamation of two chapters, and addition of a new chapter. The final content is recommended to be:

- Global Overview
- Tropical Cyclone Formation, Intensity and Structure
- Tropical Cyclone Motion
- The Tropical Cyclone and Landfall
- Seasonal Forecasting
- The Total Warning System
- Numerical Prediction Models
- Forecast and Observing Technology
- Ready Reckoner
- Bibliography

The bibliography will be expanded to become a general, tropical bibliographical resource, with submitted references being added if they are in the correct format.

It was further recommended that a forecaster's web site be established as part of the Guide Web site on which operational studies, forecasting rules and other relevant material could be posted.

Other General Recommendations

2.2.2 Following practice with the previous IWTCs, it was recommended that the next IWTC review the recommendations of the previous IWTC *in the pre-workshop documents*.

2.2.3 In order to keep an up-to-date summary of what is happening around the globe, to improve the observing, analysis and prediction of tropical cyclones, including case studies, it was recommended that a common web site be developed. It was proposed that this lie on WMO internet site (www.wmo.ch) and be linked to relevant information.

2.2.4 It was noted that many National Meteorological Services have received strong support from both governmental and private sectors. Approaches to private sector organizations, that profit from the use of weather information was encouraged, in order to obtain support for the Tropical Cyclone Programme.

2.2.5 It was recommended that the organizational structure for the next IWTC should return to the arrangement adopted at IWTC-III in which each session topic has a forecaster and a researcher rapporteur, together with an expert rapporteur for each sub-topic. The forecast rapporteurs should bring a list of issues to be discussed at a special forecaster's meeting.

2.2.6 It was recommended that the next IWTC include a subtopic on Extra-Tropical Transition. Given the level of interest about this topic and the potential for destruction from cyclones undergoing extratropical transition, it is very important that this subject receives increased attention.

2.2.7 It was recommended that each warning centre maintain a record of warning verification statistics in order to monitor their ongoing performance.

2.2.8 It was recommended that the Hanoi-Beijing GTS link be upgraded as soon as possible.

2.2.9 Much of what is contained in Recommendations A1 (III) of IWTC-III still holds true. In addition, it should be noted that the replacement of Omega radiosondes by GPS radiosondes has resulted in significantly higher costs and a reduction in the number of radiosonde soundings in a number of countries.

2.2.10. Greater access to remote sensing data from NASA Topex/Poseidon, Ocean Surface Current Radar (OSCR), Over the Horizon Radar (OHT), SSM/I, ERS and other platforms is essential in monitoring the atmospheric and oceanic environment and efforts should be made to obtain these data in real time.

2.2.11 A global database should be setup, probably on a web site so that meteorological centres who keep a range of economic and societal statistics in relation to tropical cyclone impacts can lodge their data for future analysis.

2.2.12 Studies should be undertaken to assess the economic value of a tropical cyclone warning so that funding agencies of future projects will be able to see a tangible reason to support any upgrade to the warning system. For example, improvements in track forecasting should lead to a smaller area under watch or warning, with a consequential feedback in lower preparation costs.

2.3 Recommendations for WMO

2.3.1 There is a pressing need to understand the behaviour of tropical cyclones close to the coast, at landfall and following their passage inland, especially in regard to wind and rain as highlighted in the proceedings of the IWTC-IV. IWTC-IV endorses the objectives laid out in both the USWRP and WMO/CAS World Weather Research Programme (WWRP) landfalling research project proposals. In collaboration with USWRP, the WMO WGTMR is encouraged to work through the WWRP programme to the stage of executing Forecast Demonstration Projects (FDPs) on landfalling tropical cyclones. Two potential FDPs have been suggested, wind field at landfall and precipitation. So that all can benefit from the results of these projects, information should be shared amongst other countries.

2.3.2 Improvements in tropical cyclone track predictions have been achieved in part by better use of available observations e.g. satellite radiances directly versus profile retrievals. However, future progress in 3-D and 4-D data assimilation will require so called "forward models" for each observation type. It is recommended that WMO/JSC Working Group on Numerical Experimentation (WGNE) promote a programme in which the global analysis centers would co-operate in developing and sharing these forward models with the goal of rapidly improving tropical cyclone analysis and predictions.

2.3.3 WMO should investigate with the EUMETSAT the possibility of permanently retaining a Meteosat geostationary satellite at 65° E. This would enable continuous coverage across the entire South Indian Ocean, which has been unavailable up until now.

2.3.4 There is concern amongst the meteorological centres of developing countries about the economic impact of obtaining access to the new generation geostationary satellites. WMO is requested to ensure that those countries have access to the new systems.

2.3.5 There is concern about the quality of tropical cyclone databases for best track information. In most basins, the intensity data over the past few decades have been based largely on satellite interpretation, essentially from the Dvorak technique, and a variety of pressure-wind relationships. These techniques have not been validated in most regions and databases contain no information on error statistics. Confusion also exists on the actual meaning of maximum wind due to the variety of wind-averaging times used.

It is recommended that WMO draw up guidelines to assist tropical cyclone archiving centres in keeping better quality databases including full documentation of size (i.e. radius of gale force wind) and radius of maximum winds for each individual tropical cyclone. In addition, a single archive of raw observational data should be established in each basin. This would allow the data to be made readily available for re-analysis of best tracks and other purposes.

2.3.6 Since the wind gust is the most fundamental component of the near surface tropical cyclone-induced wind, and is the wind value least influenced by surface friction, it is strongly recommended that peak gust and its time of occurrence be added to the synoptic code.

In addition, the time of occurrence and the value of the minimum pressure, and an indication of the occurrence of an eye passage be added to the synoptic code. This information is needed to determine the maximum wind-minimum central pressure relationship associated with tropical cyclones.

2.3.7 Where multiple sources of advisory information are available on the same tropical cyclone, the international media should be encouraged and given easy access to the official forecast for the region. WMO has given a specific guideline to the RSMCs in paragraph 3.4.2 c) of the proceedings of the 49th session of the Executive Council. This IWTC-IV recommendation also refers to individual countries that have tropical cyclone forecasting responsibilities.

2.4 Research and Applied Research Recommendations

2.4.1 A parametric model of precipitation associated with a landfalling storm should be developed combining:

- A short-range track and intensity forecast;
- Rainfall rates derived from satellite/radar imagery-calibrated from a rain gauge network.

2.4.2 Given the absence of any real skill in tropical cyclone intensity prediction, the meeting recommends the following:

- Collaboration between research groups working with atmospheric and oceanic models should be strongly encouraged. The existing collaboration between GFDL and other groups to develop a coupling of the GFDL model with the Princeton fine-mesh multi-level ocean model, up to the stage where the coupled model could be used operationally, is a good example;
- Applied research effort should be undertaken to develop the knowledge base and methodologies to provide skillful tools for intensification/decay prediction. A good starting point would be forecasting the correct trend.

2.4.3 A greater effort is required to better understand the physical processes in the tropical cyclone circulation and studies are recommended in:

- Air-sea exchanges in the vicinity of extreme winds, including the effect of spray cooling;
- The movement of spiral rainbands towards the center, and the formation of outer eyewalls.

2.4.4 Further research is necessary to explore the tropical cyclone genesis problem, particularly where tropical cyclones form close to coastlines or island groups. Cross-equatorial effects may need to be taken into account.

2.4.5 The Dvorak intensity analysis technique has been calibrated in the Atlantic, but the lack of observational data in other regions has caused difficulties with calibration. It is recommended that calibration or re-calibration of the Dvorak technique, and all pressure-wind relationships be undertaken in all basins.

2.4.6 The development of alternative diagnostic tools to Dvorak, using pattern recognition, in for example microwave data, should be investigated.

2.4.7 As with previous IWTCs, improvements in tropical cyclone motion forecasting rate highly amongst forecaster priorities. On average, the accuracy of dynamical model track prediction has increased. However, research needs to be undertaken to examine cases when dynamical model accuracy is poor or when there is a large amount of disagreement between the dynamical forecast models.

2.4.8 Further progress in dynamical track prediction could be achieved through improvements in horizontal and vertical resolution, model physics, data assimilation techniques, ensemble forecasts and targeted observation strategies. It is important that progress in all these facets should be maintained.

2.4.9 The simplicity and computational efficiency of barotropic models should continue to be exploited primarily for investigations of the effect of internal structure dynamics on motion, vortex-induced planetary waves, the influence on the environment and adaptive sampling strategies.

2.4.10 The usefulness of potential vorticity analyses as it applies to tropical cyclone motion should be established.

2.4.11 Investigations into the baroclinic processes associated with tropical cyclone motion should continue with careful analysis and interpretation of the influence of diabatic processes.

2.4.12 Short-term track changes impose a limitation on forecast accuracy and the mechanisms that cause them need to be identified. Investigations should continue into the effects of inner structure dynamics, interactions with adjacent mesoscale convective systems and topography.

2.4.13 The definition of maximum sustained wind speed of tropical cyclones is confusing and has different meanings in different areas. It would go a long way in the understanding of the differences if conversion factors connecting the various wind averaging periods could be computed and the results incorporated into the Global Guide on Tropical Cyclone Forecasting.

2.4.14 Parametric wind models form a basis for a range of forecast and diagnostic applications. Yet many such models are kept confidential or have not been adequately tested. The meeting recommended that a public domain parametric wind field model, fully tested and verified by peer review, be developed to provide the standard for comparison purposes.

2.4.15 Further research should be carried out to understand the physics of the interaction between upper-level troughs and the circulation of tropical cyclones.

2.4.16 Continued research should be undertaken aimed at providing improved documentation of seasonal variations of tropical cyclones, and of understanding the associated processes.

2.5 Forecasting Recommendations

2.5.1 It was generally felt that there has already been good progress made over the past in developing methods and models to forecast surge heights. However, further work is necessary for the small island situation, especially the effects of reefs. Used in a climatological way, with well-defined tropical cyclone scenarios (including worst-case envelopes) these models could be useful to estimate risks of storm surge through a dedicated data base. We recommend that the technology presently available be shared amongst countries with a need for storm surge forecasting capability.

2.5.2 Given the absence of any real skill in tropical cyclone intensity prediction (currently, the only model that has provided real-time skill above climatology and persistence is the statistical-dynamical model (SHIPS), the meeting recommends the following:

- Real time ocean data (including not only SST, but also some measure of mixed-layer depth) need to be incorporated into tropical cyclone forecasting procedures in order to improve intensity forecasts:
- Some purely dynamical models show promise in providing useful intensity forecasts. In the short term, skillful intensity forecasts could be obtained from creative uses of statistical dynamical models for a relatively low cost effort. This should be strongly encouraged.

2.5.3 All tropical cyclone forecasting centers are encouraged to adopt a systematic and integrated approach to tropical cyclone prediction, with the assistance of artificial intelligence or expert systems, or a combination of both.

2.5.4 Operational forecasters are encouraged to make use of thermodynamically derived potential intensity guidance in assessing the future intensity of a tropical cyclone.

CHAPTER 3: TOPIC 1

3. LANDFALLING CYCLONES (by K. McGuffie)

3.1 Introduction

The impact of tropical cyclones upon human society is undoubtedly greatest at the time the storm interacts with land. The landfall process is really a continuum of events and processes, rather than a well-defined time where (for example) the storm center crosses the coastline. For small island nations, the notion of coastal crossing of the storm may not apply, yet the interaction of the storm with the island and its society may be devastating. The exact definition and extent of the landfall period therefore varies substantially with location. The period around landfall is of critical relevance and the meeting confirmed this idea. The discussion of the problem was focussed on a small number of topics that relate to landfalling cyclones: maintenance and improvement of observing systems; improved understanding of the physical systems and processes involved; and forecast and warning techniques (particularly rainfall and storm surge). Enthusiasm was expressed for the research component of the USWRP whose principal focus is landfalling cyclones in the North Atlantic. The research issues being tackled by the USWRP were felt to have wide relevance to other basins although some of the forecasting issues were felt to be less generally applicable.

3.2 Storm Surge

Storm surge is often used to refer to the combination of storm surge, astronomical tide, wave set-up and wave run-up: a combination which is often referred to by engineers as 'storm tide'. The relative importance of these individual factors in the final effective height of water varies with geographical location. Wave run-up and wave setup tend to have greater relevance to island nations that does the surge (pressure and wind induced elevation of water surface). Timing of landfall is an important issue when the effect of the astronomical tide is significant, although currently, the errors associated with timing of landfall mean that most estimates of surge must be made for high tide.

The major issues identified in relation to storm surge were of technology transfer. Although some island nations have been making use of a storm surge model that includes wave setup, as well as astronomical tide and storm surge, many nations do not have the facilities to apply existing technology to the problem. The storm surge problem is, therefore, not a research issue in itself. The uncertainties associated with predictions of storm surge and wave effects are governed largely by the uncertainties in surface wind field, bottom topography and the complex effects of reefs and there is work to be done in these areas. The effective use of a real time storm surge model by forecasters, particularly where resources are scarce, is difficult because of these uncertainties in the boundary conditions.

The best approach is likely to be the construction of a climatology of storm surge events based on a parametric model which gives an envelope of possible outcomes for given ranges of track, intensity and size. These studies are also valuable for disaster management and preparedness. There is a need for a focussed effort at providing a basic level of these technologies to nations with limited facilities to conduct their own surge evaluations.

3.3 Rainfall

Rainfall, by causing flooding and landslides, is a major cause of death and destruction associated with tropical cyclones, however its attendant ability to break drought conditions in many

countries can also be a beneficial consequence. There is still little skill in forecasting precipitation from tropical cyclones and the very small variations in rainfall distribution can have very large influences on the resulting runoff. The problem of rainfall from tropical cyclones has been raised and discussed at previous RNTC meetings (e.g. ITWC-III report, Chapter 7).

The problem remains difficult to solve but confidence was expressed that good progress is being, and will be made on this issue. As well as the difficulties associated with the prediction of rainfall patterns associated with a storm which may be undergoing significant structural changes, the verification problem remains significant since effective rainfall networks which may be used for forecast verification are unusual. Although some models (e.g. GFDL) are beginning to provide effective precipitation forecasts, even small errors in the final track can have critical effects on the final rainfall distribution pattern as it falls in different hydrological basins (e.g. Hurricane Pauline in Mexico in 1997).

There was also support for the use of an engineering approach to derive a parametric model of precipitation that could be used to provide first order descriptions of precipitation distribution within storms. Such a model would need to be based on results from satellite observations of precipitation and upon gauge networks and radar. Preliminary steps in tackling the rainfall problem have been proposed for Guam.

Adequate observing systems are crucial during the period around landfall. The need for maintenance of the present upper air and surface observation network was emphasized. There was a plea for increased availability of TOPEX data to provide information on ocean mixed layer heat content. The data collection issue can also be extended to the post storm period. The need for the coordinated collection of a database on landfalling cyclones (e.g. aircraft, satellite and coastal radar data) was promoted. It was noted that some agencies (e.g. National Hurricane Center, US National Climate Data Center) are already well advanced in homogenizing existing archive material with a view to making use of available computer and network technology to distribute these data.

3.4 Surface wind field

As a storm comes ashore or interacts with islands, many physical changes in the storm structure can be induced. ITWC-III reported on the problems associated with the tropical cyclone wind field at landfall. Wind transients, gusts, meso-vortex structures and vortex breakdown confound intensity estimates and these changes in structure have been implicated in severe damage that has resulted from some tropical cyclones.

The structure of the eye wall, the role of topography in modifying the storm structure and the effect of orography on the storm track are current research issues and progress is being made on these topics.

The ability to forecast potential tornado formation within storms, at and following landfall is also a goal for the research community. For forecasters, the issue is important because some storms may spawn only a handful of tornadoes, whereas others may produce very many more.

A number of studies have indicated the role of structural changes in damage caused by landfalling cyclones. Recent cyclones (Hurricanes Hugo 1989, Andrew 1992, Opal 1995 and Fran 1996) have caused significant damage as they moved inland in the United States and have underlined the importance of studying the wind field evolution. The rate of decay of storms as they pass inland is one in which there is little guidance. Currently only one operational numerical model and an empirical model are available for this component of the landfall process. At this stage it is unclear how well these models predict the evolution of the surface wind field. The structure of the storm and in particular its influence on the nature of the surface wind field was confirmed as a major research priority.

3.5 Summary

The major issues in this topic area are surface wind field, precipitation and storm surge. The latter is widely regarded as a technology transfer issue and steps must be taken to improve

access to effective surge assessment techniques. The concept of a forecast demonstration project as part of the World Weather Research Program (WWRP) (as collaboration between TMRP and USWRP) was proposed. Two potential projects were identified to be:

- specification of wind field at landfall which is applicable to studies of storm surge and also to studies of the nature of induced damage;
- forecast of rainfall at landfall is a major forecasting issue requiring both improvements in forecasting techniques and verification techniques.

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CHAPTER 4: TOPIC 2

4. TROPICAL CYCLONE INTENSITY AND STRUCTURE (by C. Landsea)

Understanding tropical cyclone intensity changes and being able to skilfully forecast these variations are the greatest challenges facing tropical cyclone meteorologists as we head into the 21st century. This report summarizes the rapporteurs' reports and the discussions on this challenging topic from the Fourth WMO International Workshop on Tropical Cyclones (IWTC-IV) held in Haikou, China from 21-30 April, 1998.

4.1 The Tropical Cyclone Lifecycle

To best put into context our increasing knowledge of tropical cyclone intensity changes, we first start with a conceptual picture of the lifecycle of the tropical cyclone (Figure 4.1). Broadly, the tropical cyclone lifecycle can be put into four stages: genesis, intensification, maturity and decay.

Genesis: This refers to the first point where a low-level mesoscale core circulation with organized convection occurs. This is distinct from monsoon depressions/monsoon gyres, which lack a mesoscale center of deep convection and small radius of maximum winds, and distinct as well from easterly waves, which lack a closed circulation.

Intensification: In general, this is where the winds in the inner core (within around 100 km) spin up and the central pressure drops. When such intensification is rapid (say greater than 25 m/s in maximum sustained surface winds or 40 hPa in central pressure in one day), this becomes a chief concern to forecasters and emergency managers and is very much unforecastable at this time.

Maturity: This is when the tropical cyclone is well-developed and has maximum sustained surface winds of around 50 m/s or central pressures of around 950 hPa or lower, though the majority of tropical cyclones do not reach this stage. At this point, substantial concentric eyewall cycles affecting the intensity may occur with timescales on the order of a day, but extremely variable.

Decay: This portion of the lifecycle involves the spin down of the strongest winds, though there are indications that the size of the storm - perhaps measured in the radius of gale-force winds - can continue to increase even while the inner core is weakening. Decay occurs when the tropical cyclone moves over land, encounters strong vertical wind shear from a synoptic scale upper to mid-tropospheric trough, progresses over cool (less than around 26°C) sea surface temperatures (SSTs), and/or is transformed/absorbed by extratropical baroclinic storm systems.

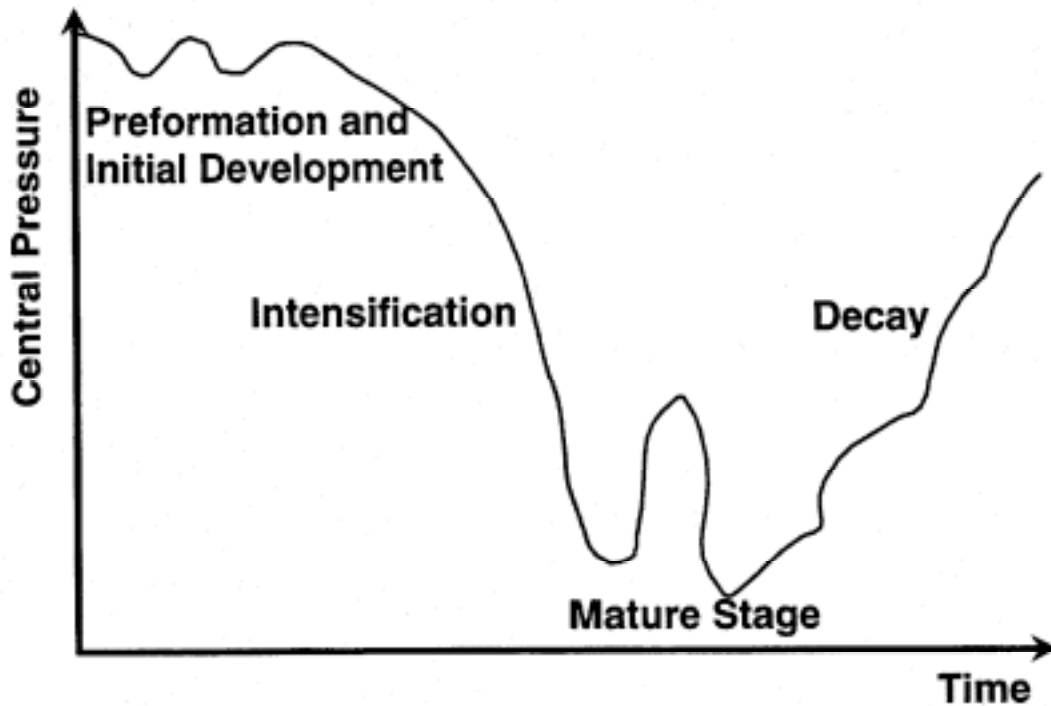


Figure 4.1: Tropical cyclone intensity stages used in this report, shown relative to a schematic time history of central pressure.

4.2. Physical Scales of the Tropical Cyclone

As described earlier, intensity changes are the variations of surface winds in the inner core (within 100 km) of the tropical cyclone (Figure 4.2). We must emphasize how small in the horizontal the scale is for intensity changes as the typical radius of maximum winds is on the order of 10s of km. This is definitely a mesoscale phenomenon. However, the outer core (outside of 100 km radius) can extend at times several hundred kilometers from the storm center. As the tropical cyclone intensifies, the cyclonic core becomes inertially stable and exhibits strong radial windshear (that the infamous "in-up-and-out" phrase that Dr. Bill Gray coined so well describes). In this environment, convective processes dominate and the strong radial shear tends to produce a more or less symmetric development of the vortex. Air-sea interactions are important in both the inner and outer core of the tropical cyclone because the tropical cyclone must obtain the vast majority of its heat and moisture inputs for its thermodynamic heat engine from the ocean surface. However, it is in the region of the inner core where high winds produce a spray layer as an interface between the ocean and atmosphere that acts as a complicating factor into the understanding of this interaction. Another consideration is that the inner core is only a small proportion (on the order of 10% or less) of the total angular momentum of the tropical cyclone, as most resides in the larger outer core circulation. It is relatively unknown how the outer core relates to intensity change at least partially because of the lack of documentation of the true tropical cyclone size. This outer core has relatively low inertial stability, so that other synoptic features including mesoscale convective systems dominate over convective processes and thus can affect the structure of the outer core circulation. The upper tropospheric outflow layer has the best opportunity for nearby synoptic scale features (such as tropical upper tropospheric troughs) to influence the inner core intensity via a complicated mix of debilitating vertical wind shear and enhancing eddy angular momentum flux convergences.

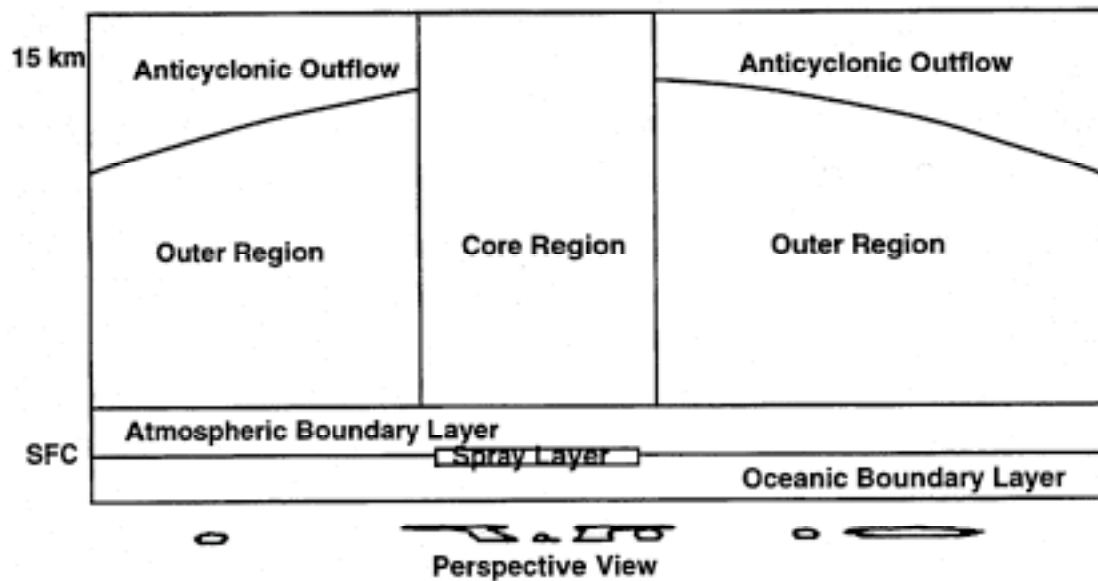


Figure 4.2: Schematic of the major regions in a tropical cyclone, based on physical scaling principles.

4.3 Summary of the Main Issues for Intensity Change

The tropical cyclone intensity problem involves the interaction between an evolving tropical cyclone and its environment, which also is spatially and temporally varying. One perspective would consider these four factors in defining the problem:

1. External forcing from the tropical cyclone's environment;
2. Interactions between the tropical cyclone and its environment which causes an environmental response;
3. Forcing from within due to internal dynamics in the tropical cyclone's inner core; and,
4. Interactions between the inner and outer cores of the tropical cyclone.

Forecasting intensity change thus requires a knowledge of processes both within and external to the tropical cyclone. Skillful prediction of all of these factors is as uncertain as the evolution of the tropical cyclone itself. There appears to be a great need to synthesize how all of these factors relate and interact together to produce changes in intensity.

4.4 Definition of Intensity and Intensity Databases

Intensity of a tropical cyclone is operationally defined as the maximum sustained (either a 1 min, 3 min or 10 min average, depending upon the region) surface (10 m) wind speed that occurs anywhere in the tropical cyclone wind field. This definition takes into account any asymmetries induced by the translation motion of the tropical cyclone. Tropical cyclone intensity can also be measured by the minimum central pressure, which is a more conservative variable and so can be much easier to estimate. However, because the winds are related to the pressure gradient and not the pressure itself, a one-to-one correspondence of pressure to wind (i.e. a "wind-pressure relationship") may not be accurate especially for very small or very large tropical cyclones. The public and emergency managers make use of the maximum sustained wind speeds (or more appropriately on the estimated short period - a few seconds - gusts) for tropical cyclone preparations as it is the wind stress on ground surfaces that causes impacts and damages.

Variations from basin to basin (and even within a basin) of intensity values can be problematic when one group uses, for example, a 1 minute maximum wind speed and another uses a 10 minute value. Such differences will be difficult (if not impossible) to change to one common format, but observing system technology can be adapted to either. Additionally, there are available empirical factors that allow for conversion from one standard to the next. Finally, there are questions about what the wind speed output from numerical models means in terms of averaging time that must be addressed for their use in intensity prediction.

Archives of tropical cyclone intensity (in the "best track" data sets) typically have been saved in all basins as the maximum sustained winds. Numerous suggestions were made at the workshop to also routinely archive more intensity and structure related values, such as the central pressure and, where it would be accurately measured, values of the radius of maximum wind (RMW) and the size of the tropical cyclone (radius of 18 m/s, 33 m/s, 50 m/s winds). There are also efforts underway to perform a "re-analysis" of tropical cyclone archives to take into account data not available originally, to extend the records back further in time, to remove biases in the databases and to use today's analysis techniques on yesterday's data. Such efforts should also endeavour to provide a raw database of tropical cyclone observations of intensity and position (aircraft reconnaissance, ships, buoys, land stations, satellite and radar) to allow users of the best tracks to see the original data from which the best tracks were analyzed.

Archives of intensity allow, for example, development of statistical methods for forecasting intensity as well as the verification of predictions of both statistical and numerical model output. Numerous interests utilize these archives for studies of risk assessment and vulnerability, including computations of frequency of maximum wind speeds above certain thresholds along coastal regions. Other uses of the archives include studies of tropical cyclone climate variability. Having the highest quality databases with as much information on the inner core intensity and outer core winds is of benefit to all of the listed parties.

4.5 Analyzing Intensity and Structure

Currently, the Dvorak technique (a satellite imagery pattern recognition scheme developed during the 1970s) is the main tool for nearly all of the tropical cyclone basin forecasting centers. This technique, while not being a completely objective method, does provide quite consistent intensity estimates from one analyst to the next. (Note that there is an objective Dvorak technique that uses infrared pixel count information, but it is only useful for at least hurricane force [≥ 33 m/s] tropical cyclones.) While the Dvorak technique has only been calibrated for use in the Northwest Pacific and Atlantic basins, other basins make extensive use of the technique.

Alternatively to Dvorak, the Atlantic basin has exclusive use of aircraft reconnaissance for routine measurements of intensity. Even in the Atlantic, this tool suffers from the uncertainty in how to properly convert the flight level wind measurements down to the surface as sustained winds. With the recent advent of the new global positioning system (GPS) dropwindsonde that can collect high resolution, highly accurate wind and pressure information even under extremely violent and wet conditions, there may soon be better estimates of how to calculate this extrapolation in the absence of sonde information.

Much discussion centered on finding additional tools for measuring the current intensity of tropical cyclones. The first of which is understanding what short term (hourly or finer resolution) variations in the objective Dvorak calculations imply with respect to the behaviour of tropical cyclone winds. Secondly, analysis methods currently being developed that make use of other spectral windows (such as the microwave SSM/I sensor) may offer an additional source of intensity estimates, particularly at the lower end of the tropical cyclone intensities where the Dvorak technique has more uncertainty. Finally, it may be possible within the next few years for unmanned autonomous aircraft to also provide direct measurements of the tropical cyclone winds and central pressure. However, this capability has not yet been proven.

Knowing the outer core wind structure of the tropical cyclone has perhaps more uncertainty than the inner core winds. Until recently, estimates of gale force wind radii were limited to information from the occasional ship or buoy observations. Developments in the last few years have improved this situation primarily through the use of satellite data. High density (around one

measurement for every 1° latitude and longitude), low level (925 to 750 hPa) cloud drift wind data around the periphery of the tropical cyclone along with direct measurements of surface wind conditions via scatterometer instrumentation have allowed for better estimates of these outer wind conditions to be made. Additionally, the unmanned autonomous aircraft have a great potential for monitoring this key parameter of tropical cyclone size.

Both intensity and outer core structure estimates, when many disparate kinds of observations are available, benefit when an analysis scheme is utilized that extrapolates the data to a common framework of averaging time and elevation.

4.6 Environmental Forcings

Environmental forcing of tropical cyclones is defined here to include changes induced by the oceanic environment over which tropical cyclones develop and gain their energy from as well as the surrounding tropospheric (and stratospheric) environment.

4.6.1 Air-Sea Interactions

The tropical cyclone is a phenomenon that can be thought of as a heat engine that obtains its energy inputs through latent and sensible heat flux from the ocean. However this energy flux also transfers momentum flux from the tropical cyclone to the ocean at the atmosphere-ocean interface; thus the tropical cyclone only "feels" the ocean surface. So while SST have been demonstrated to be an extremely important factor for genesis and intensification, new results are showing that the subsurface conditions (i.e. the oceanic mixed layer) are extremely variable even for constant SST and can play a role in intensity change. Because of frictionally forced upwelling and increased turbulent mixing, cooler subsurface waters are brought to the surface in the tropical cyclone core. Rapid changes in mesoscale structure and intensity are possible in response to forcing from SST changes under the tropical cyclone core region.

A key uncertainty for understanding and forecasting tropical cyclone intensity change is knowledge of air-sea conditions in very strong wind conditions and what values to use, for example, for coefficients of momentum and heat exchange. Further complicating the issue is this. At and above gale force (greater than 18 m/s) the air-sea temperature contrast - typically the surface air temperature is 1°C cooler than the SST in quiescent tropical ocean conditions increases to 2-4°C and has a completely unknown value for wind speeds of 50 m/s and greater. Lastly, within hurricane force (greater than 33 m/s) winds, a third fluid - the spray layer - develops and may also cause alterations in the ability of the tropical cyclone to extract energy from the ocean. These issues require much more study before their implications will be fully known to the forecasting of intensity.

Measurements of the tropical ocean have traditionally been made through a mix of ship and buoy observations blended with satellite measurements of the ocean skin temperatures to provide global estimates of SSTs. However, as we are beginning to realize that SSTs are only part of the necessary oceanic contribution, additional measurements of the subsurface temperatures and currents are desperately needed. The measurements of the oceanic mixed layer can be partially derived from the satellite TOPEX radar altimetry data that gives extremely accurate measurements of sea surface height. Subsurface measurements may also be gained from tethered buoys and from airborne expendable bathythermographs (AXBTs), though these instrumental data are primarily experimental in nature and not routinely available.

4.6.2 Atmospheric Interactions

The environmental atmospheric interactions have primarily been viewed as dynamic forcing from upper tropospheric features, though there are beginning to be indications that the dynamic forcing may be acting in concert with thermodynamic variations. Upper tropospheric troughs (or potential vorticity [PV] anomalies, if you prefer) are usually either relatively shallow tropical upper tropospheric troughs (TUTTs or upper lows) or the deeper, baroclinic mid-latitude troughs. There is strong evidence that these troughs interact with tropical cyclones to produce a large variation in tropical cyclone intensity change. Troughs can provide unfavorable vertical wind shear (which may disrupt the structure of the storm by reducing convection up-shear and

enhancing convection down-shear and/or by advecting away the latent heat released in convection) at the same time as providing favorable eddy angular momentum fluxes (which cause widespread enhancement of storm scale convection). Understanding the complexity of these competing interactions requires data through the whole depth of the troposphere (and perhaps in to the lower stratosphere) in order to define the key atmospheric features, but data can be quite limited over the open oceans.

The lack of knowledge of which troughs enhance tropical cyclone intensity and which troughs cause tropical cyclone decay has severely limited the ability of forecasters to improve intensity predictions. One suggestion that may prove to be valuable is that intensifying troughs may be ones small enough and in the right location to provide the favorable interactions without also bringing along the destructive vertical wind shear.

It almost goes without saying that continued in-depth research is needed to sort out the various contributions that these troughs force. We need to know not only what the effects are, but also we need to know the mechanisms of why such changes take place. There are some indications that these trough interactions, which had been thought of as being just dynamically-induced changes, may also accompany corresponding changes to the thermodynamics. For example, strong vertical shear from an upper trough may also be causing an increase in the moist static stability, thus inhibiting deep convection.

One topic that did not receive much initial discussion in the pre-conference Rapporteur Reports, but did generate quite a bit of interest at the workshop itself was extratropical transition. This is a key problem for countries in the mid-latitude belt (such as Australia, Canada, China, Japan and New Zealand). Forecasters there need to determine whether a tropical cyclone will retain its intensity into the mid-latitude regions, whether it will decay into a weak system because of increased vertical shear and cooler SSTs, or whether it will start to transform into an extratropical storm system with characteristics (and impacts) of both types of systems. Such keen interest dictated that increased research and forecasting emphasis be placed on these systems and that more formal presentations/discussions be carried out at the next IWTC meeting.

4.6.3 *Tropical Cyclone's Feedback to the Environment*

While much focus has been upon the effect that the large-scale environment has upon tropical cyclone intensity change, there is a not insignificant feedback in the opposite direction that may then again affect tropical cyclone activity. Two effects in particular have been examined. The first is that the probabilities for tropical cyclone genesis are enhanced to the east and equator-ward side of existing tropical cyclones. Modelling work suggests that this is due to Rossby wave dispersion from the preexisting tropical cyclone. Secondly, as mentioned above, the tropical cyclone induces a SST cooling by turbulent mixing and by frictional upwelling of cooler subsurface water. This effect is enhanced by more intense winds, slower tropical cyclone translation speed and shallower mixed layers. When such cooling becomes significant below the tropical cyclone's inner core, a self-induced brake is invoked on intensification. The wake of cool water behind tropical cyclones can also affect intensification rates of other storms that happen to also cross the cool wake.

4.7 *Internal Dynamics*

Through analyses of aircraft flight level data, radar imagery and theoretical modelling, we are beginning to see concrete evidence of mesoscale vortices embedded within the eyewall (i.e. polygonal eyewalls) of severe tropical cyclones. Such mesoscale vortices, which may have a horizontal scale of only a few kilometers, can dramatically affect the wind/mass field and may be responsible for localized regions of extreme destruction beyond that expected from the larger scale flow. Knowing how often and under what conditions such events occur would be extremely valuable information for the tropical cyclone forecaster. Suggestions for their existence include barotropic instability of the inner core wind field as well as Rossby waves forming and amplifying along the radius of maximum winds. Both of which may be induced internally, without forcing needed by the external environment.

A second feature that may be ascribed to internal dynamics is the concentric eyewall and its cyclic nature. Strong tropical cyclones (greater than about 50 m/s) often are observed to have concentric eyewalls one with radius on the order of 5-25 km and the other one further out at a radius of 25-100 km. The outer eyewall will contract many times, causing weakening of the inner eyewall, and eventually replace the inner eyewall. While this is occurring, the tropical cyclone will weaken as the inner eyewall is being destroyed and then the cyclone may return to its previous intensity or sometimes even become stronger. These cycles may be externally induced, but it is just as likely at this point that they may be features intrinsic to strong tropical cyclones.

4.8 Outer Core Structure

The outer core structure or size of a tropical cyclone is very important from a practical aspect of forecasting as it affects the amount of time for preparations for landfall to be done. Typically, the preparations for landfalling tropical cyclones are taken between the time when watches/warnings for an area are issued and when the first sustained gale force winds occur.

Unfortunately, the topic of outer core structure is nearly a complete unknown in both theoretical and forecasting perspectives, again because of the lack of ground truth. The only basics known are that in general the size of the tropical cyclone wind field expands as it matures and moves poleward and that the increases in the size of a tropical cyclone are not related well to its intensity. Questions abound regarding outer core: Under what conditions would the outer core strength increase in concert with the inner core intensity and when would they act independently? How do environmental features of the air-sea boundary and upper troughs affect the size of the storm? Do conditions at genesis of a tropical cyclone dictate size? How do other atmospheric features such as mesoscale convective complexes, monsoon troughs and easterly waves affect the size?

4.9 Maximum Potential Intensity

Maximum potential intensity (MPI) is the theoretical limit that a tropical cyclone may achieve based purely upon thermodynamical considerations. While some measurements of MPI have been derived from SSTs alone, it is recognized that MPI should be based upon both SST and the overlying atmosphere. While only a few percent of tropical cyclones approach the climatological MPI, it may be that a much larger proportion of tropical cyclones reach their MPI but this is difficult to determine without reliable local SST and atmospheric stability data.

Suggestions were made that suggests that the act of tropical cyclogenesis also serves to reduce the local MPI by slightly stabilizing the surrounding atmosphere. Regardless of these complications, the possibility emerged for MPI to be utilized as an actual forecasting tool to help provide upper limit bounds for individual tropical cyclones. However, use of this technique becomes problematic in areas of sharp SST gradient (e.g. north of the Gulf Stream and the Kurishio Current) where MPI goes to "zero" much quicker than the tropical cyclones tend to decay.

4.10 Genesis

We are beginning to understand the physics of genesis as the interplay of a variety of mesoscale processes occurring under synoptically favorable conditions. Given that there are preexisting conditions of warm ($\geq 26^{\circ}\text{C}$) waters, conditionally moist unstable atmosphere, relatively moist mid-tropospheric values, a lower tropospheric disturbance of at least modest vorticity and convergence, a distance of a few hundred kilometers from the equator, and relatively low ($\leq 10\text{-}15$ m/s) tropospheric vertical wind shear, then there is a possibility (but no guarantee) that tropical cyclogenesis will occur. At this point, a convective event such as an individual mesoscale convective system may produce a mesoscale convective vortex - typically in the trailing stratiform region with maximum vorticity in the middle troposphere. Somehow (and this is where much research efforts have been geared) the mesoscale convective vortex's vorticity reaches the surface, a resumption of deep convection occurs along with noticeable sea level pressure drop and a beginning of swirling winds at the surface - genesis has occurred.

At previous IWTC meetings, little emphasis had been placed upon improved understanding and forecasting tropical cyclogenesis. Indeed, at IWTC-I nearly all forecasting

centers indicated that forecasting genesis was "not perceived to be important". However, in the intervening years, perhaps because of increased pressures to provide 3 to 5 day forecasts and perhaps because improvements in tropical cyclone track have allowed other concerns to become more prominent, at this meeting there was nearly unanimous consent that forecasting genesis had become "an important problem".

While global numerical models do produce tropical cyclone vortices regularly in real-time, there has been little documentation as to the skill of such forecasts. Anecdotal evidence suggests that the global models do correctly indicate that genesis will occur (though not with the correct timing), but that there exists a large false-alarm rate with many spun up model vortices that do not actually occur. Efforts should be geared toward better understanding the mechanisms leading to genesis and then providing skillful methods (statistical and numerical) that would assist in its prediction.

4.11 Intensity Forecast Models

Forecasting intensity change of tropical cyclones - especially rapid intensification - is a great challenge. For numerical models to successfully predict intensity change, detailed physics with very fine resolution in a coupled ocean-atmosphere model framework may be necessary. What are the minimum model resolutions required to produce realistic aspects of tropical cyclone intensity and structure? With a very fine grid spacing, how would one properly initialize such a model? Coupled models are likely to be useful, but parameterization of air-sea interaction is untested at high wind speeds. Correct heat and momentum fluxes are both crucial to resolve the interaction problem. For proper validation of such models, highly accurate "best track" records are needed, perhaps with augmented information on the size of tropical cyclones as well.

Because of all of these complexities, there is still much room for statistical modelling of intensity - especially since they are relatively cheap (both in actual cost and in man-hours) to develop. We should be reminded that the only current model that is making skillful, real-time forecasts (i.e. able to improve over the performance of the climatology and persistence model SHIFOR) is a statistical-dynamical model - SHIPS. (However, there are some indications that at long-leads around 72 h - that the dynamical model GFDL is becoming skillful. More real-time testing is needed.) It took 20 years for such combined statistical-dynamical models to be exceeded for track forecasting. While it certainly will not take as long for intensity, strong efforts are recommended in both statistical modelling to tackle the very difficult problem of intensity change.

4.12. Summary

Reiterating a point made earlier, a great need exists to synthesize the various factors (air-sea interactions, atmospheric forcings, internal dynamics and interactions with the outer core) that go into tropical cyclone intensity change. This is inherently a much more complex issue than tropical cyclone motion because of the interactions of the scales involved. Focuses upon just one mechanism for intensity change are thus perhaps somewhat misguided and need to be steered toward a look at all pertinent factors and the relative weighting of each. Such synthesized understanding appears to be a crucial groundwork for truly having skillful intensity forecasts.

CHAPTER 5: TOPIC 3

5. TROPICAL CYCLONE MOTION (by P. Harr)

The highest priority recommendations of IWTC-III specified continuation of tropical cyclone motion studies. During the period since IWTC-III, significant research has been conducted in many aspects of tropical cyclone motion and research results are being utilized in forecast offices, which has resulted in declining forecast track errors.

The tropical cyclone (TC) motion session at IWTC-IV contained reports on environment and small-scale interactions, and on barotropic and baroclinic processes that are involved in TC motion. Each topic is summarized in the following sections. Following each summary, specific issues are compiled along with significant discussion points that were raised in either plenary or working group discussion sessions. A bibliography of relevant studies of TC motion is contained at the end of the summary.

5.1 Environmental Interactions

On the synoptic scale, combinations of various tropospheric circulation systems comprise the environment of the TC. Since the spatial scales of these systems are generally larger than the TC, the TC has often been considered as being steered by the mid-tropospheric flow defined by the combination of the environmental features. However, recent studies suggest a two-way interaction between the TC and the environment that can alter the steering and then the movement of the TC. Because many of the environmental influences on TC motion are related directly to various barotropic or baroclinic aspects of the TC and the environment in which it is embedded, there was some overlap in the discussions of these topics. Specific issues that are common to the three topics of environmental influences, baroclinic processes, and barotropic processes are mentioned in this section but detailed summary is reserved for inclusion in sections where they apply to specific atmospheric processes.

Observed TC motion has been found to differ from a pure steering current by an amount that is defined as the propagation vector (Elsberry 1990). This difference has been studied extensively in a theoretical and model framework of advection of planetary vorticity by the TC circulation, which is referred to as the beta effect. Advection of planetary vorticity by the primary TC circulation has been found to produce counter-rotating gyres that induce a flow across the TC center that may correspond to the propagation vector. However, there has been little success in identifying in observational data sets a one-to-one relationship between propagation vectors and the beta-effect induced flow over the TC center.

The lack of direct observational evidence of the beta-gyre contribution to TC motion can be attributed directly to two specific issues. The first issue is the separation of the TC vortex from the environment in which it is embedded such that interactions between the two circulations can be identified. A second issue is to define what specific observational evidence is required and how can these observations be obtained.

Although full discussion of the effect of baroclinic processes on TC motion is reserved for the next section, there is a significant environmental influence on TC motion from baroclinic systems. Vertical variations of wind and vorticity imply horizontal gradients of temperature and non-uniform potential vorticity (PV) distributions. Recent studies by Wu and Emanuel (1995a,b) and Shapiro (1996) indicate that a TC tends to move towards an area of maximum PV anomaly.

However, most investigations of the effect of PV anomalies on TC motion have concentrated over subtropical regions where the PV distributions can be influenced significantly by various factors. Little study has been done to assess the importance of PV distributions over tropical latitudes where the tropospheric distribution of PV is more uniform.

Other environmental influences have been studied recently. These include the advection of planetary momentum by the environment into the TC during periods of recurvature.

Other studies have addressed the acceleration of the TC during extratropical transition in the context of a diabatically-driven anticyclone that is located downstream of the transitioning TC and also capture of the TC by cold fronts.

Apart from the environmental influence on the TC motion is the fact that the TC may modify the environment thereby altering the subsequent motion of the TC. Generation of a trailing anticyclone via Rossby-wave dispersion is one such mechanism by which the TC modified the environment. Carr and Elsberry (1995) discuss sudden track changes due to the development of a peripheral anticyclone to the southeast of the TC. An important issue is related to differences in depiction of the peripheral anticyclone between numerical models, which may be due to differences in how the vortex structure is represented in the model.

A study by Wang and Li (1995) examined the modified beta-effect response associated with a vortex in environmental shear and found that when in cyclonic shear the wave number one beta gyres give up energy to the environment. Therefore, the vortex in cyclonic shear has a smaller beta-effect deflection while a vortex in anticyclonic shear has a larger deflection. Here, there is an implication that careful analysis of the environmental shear is important to define the appropriate vortex response.

5.1.1 *Issues and Discussion*

Discussion points related to items (1) and (2) are reserved for the section on barotropic processes and items for (3) are included in the section on baroclinic processes.

- (a) There is an intrinsic problem in interpreting the motion of a TC due to certain environmental influences because of the difficulty in separating the vortex circulation from the environment circulation.
- (b) There is a lack of observational data sets that address the identification and validation of the beta-effect contribution to TC motion.
- (c) There is a need to establish fully the extent to which PV reasoning, which includes inversion techniques and their associated components, is applicable to TC motion.
- (d) The peripheral anticyclone can turn a TC poleward if it becomes the dominant steering influence. Therefore, it is necessary to define how the anticyclone might be related to outer vortex structure so it can be depicted consistently in numerical models.
- (e) Accurate diagnosis of environmental shear could be necessary to assess the degree to which deflection from the uniform beta effect might occur.

5.2 Baroclinic effects on motion

Since IWTC-III there have been many studies of the baroclinic effects on TC motion. The first order effect of vertical shear on an initially barotropic vortex is to tilt the vortex, which induces compensating thermodynamic effects to maintain hydrostatic and geostrophic balance. Jones (1995) showed that the vertical interaction causes the upper and lower level vortex centers to rotate around a mid-level center. Furthermore, the rotation rate depends on the Rossby penetration depth.

Other studies examined the influence of a baroclinic vortex in vertical shear. Wu and Emanuel (1993) examined the influence of upper-level negative PV anomalies on the steering flow and found that this resulted in a leftward drift relative to the vertical shear. Wang and Holland (1996) also examined a cyclonic vortex that is capped by an anticyclone circulation and found that the vertical differential beta drift may induce vertical shearing of the vortex.

Therefore, diabatic heating is necessary to maintain the baroclinic structure. Wang and Holland then found that the beta drift tends to be poleward in this case. The interaction between

heating and circulation may result in convective asymmetries that could induce asymmetric divergent flow across the vortex thereby affecting the TC motion.

The application of PV thinking to diagnosis of the baroclinic effects on TC motion has promise for future study. In particular, new piecewise inversion techniques such as defined by Shapiro (1996) could be used to diagnose contributions of environmental influences on TC motion. Wu and Emanuel (1995a,b) have also used a piecewise PV inversion technique to evaluate the influence of upper- and lower-level PV anomalies in TC motion.

5.2.1 Issues and Discussion

- (a) The development and structure of the upper-level anticyclone over a TC in a research model depends on diabatic heating and convective momentum transports. Therefore, it is necessary to understand fully how a cumulus parameterization scheme affects the vortex structure and the TC motion. The depth of the anticyclone aloft may influence the response to vertical shear. Therefore, it may be necessary to compare and contrast simulations that use various moist physics representations to assess impact properly.
- (b) The application of PV analysis to TC motion should be established. Discussion concentrated on the issue that emphasis should be placed on where PV anomalies that may influence TC motion originate. Furthermore, if there is a strong interaction between motion and PV anomalies, what must be observed? Also, the affect of the TC on the PV anomalies must be examined. For example, if PV anomalies are advectively produced or diabatically generated, there are implications for diagnosis as related to TC motion.

5.3 Barotropic processes

The study of barotropic processes has resulted in significant contributions to our understanding of various aspects of TC motion. Furthermore, barotropic models have provided a sound basis for track forecasting and they continue to play a leading role in the development of ensemble forecast techniques for TC motion. The forecast aspect of barotropic models will be addressed in the section on prediction.

5.3.1 Theoretical and numerical studies

The contribution of wave number-one relative vorticity asymmetries to TC motion was summarized in the section on environmental influences. However, specific issues related to this topic are discussed in the issues and discussion subsection. Important research aspects associated with the beta-effect contribution to TC motion are related to the energy transfer between the axisymmetric circulation and the wave number-one asymmetries (Wang and Li 1995). This study and the studies of Kraus et al. (1995), Li and Wang (1996), and Wang et al. (1997), which examine the effect of large-scale flow deformations on the structure of the vortex asymmetries, have important implications for detection of the basic environmental conditions in which the TC is embedded.

Internal vortex dynamics have been investigated using barotropic dynamics concepts. Studies of vortex Rossby waves (e.g., M. Montgomery and Kallenbach 1997) have importance to vortex structure (spiral bands, concentric eyewall cycles) and motion.

Barotropic studies are important for investigating the dynamics associated with binary vortex interactions from the TC scale to interaction with synoptic scale monsoon gyres. Carr et al. (1997) have extended the notion of binary vortex interaction to include semi-direct and indirect interactions. In these cases, track deflections occur even though the separation distances are too large for direct interaction. This appears to be an area of study that is ready for direct testing as a forecast tool.

Barotropic processes have been investigated in conjunction with studies of orographic influences on TC motion. Zehnder and Reeder (1997) find that deflection of air over topography

results in horizontal convergence and divergence patterns that modify the wave number-one asymmetries.

Barotropic models have important applications in sensitivity studies to define data requirements by their ability to resolve the environment such that identification/validation of the beta-effect on TC motion may be obtained. Barotropic models also have important roles in development of synthetic vortices for initializing forecast models and also as a basis for ensemble forecast systems.

5.3.2 *Issues and discussion*

- (a) There has been a lack of identification/validation of the beta-effect on TC motion. Observational studies have not identified a one-to-one relationship between propagation vectors and the deflection due to the beta effect.
- (b) Working group discussions were centered on continued and improved use of new observational technologies to try and improve analysis quality that would be crucial for detecting evidence of beta-effect deflection. Perhaps observation system simulation experiments may be able to contribute to the specification of observation requirements.
- (c) A related aspect to issue (1) is the difficulty in separating the vortex and environment circulations. Several discussions focused on continued experimentation with techniques such as that defined by Kurihara et al. (1993-1995) to examine methodologies for separation of the circulations and the consequences of their interactions.
- (d) It appears that barotropic modelling has great utility for ensemble prediction of TC motion. Discussion centered on the fact that although barotropic models might have larger systematic errors, their simplicity and computational efficiency continue to hold some advantage for use in ensemble prediction, particularly with regard to generation of initial perturbations.

5.4 Small-scale effects on motion

Tropical cyclones often experience track meanders that vary in period and distance (Holland and Lander 1993). Meanders are often not predicted well since short-period track fluctuations can be confused with longer-term track changes or vice versa. Therefore, track meanders can place a short-term limitation on forecast accuracy.

A suggested mechanism that may be responsible for track meanders might be the vortex Rossby wave that acts to change the inner vortex structure. A basic question would then be whether inner-core structure changes, which have been examined with respect to intensity, also affect motion?

Midlevel vortices that have been identified within a stratiform region of mesoscale convective systems (MCSS) have also been examined with respect to inducing small-scale influences on TC motion. Lander and Holland (1993) assumed that an MCS adjacent to a TC had a substantial midlevel vortex and used a barotropic model to show that a combined TCMCS interaction could cause track deflections similar to those observed. Harr and Elsberry (1996) documented the midlevel vortex associated with an MCS adjacent to Typhoon (TY) Robyn during TCM-93. Their study concluded that the large differences between the strengths, sizes, and vertical extents of the MCS and Robyn circulations dictated that an interaction between the circulations could not have been responsible for the observed change in speed and direction of TY Robyn. However, this study may have produced more questions with regard to small-scale interactions. These questions are related to the sensitivities associated with the beneficial TC environment that contains saturated conditions and low-level convergence and detrimental conditions due to the large midlevel shear. It appears that the vorticity initially associated with the MCS becomes filamented due to shear and the question remains can this vorticity contribute to a track change?

5.4.1 Issues and discussion

- (a) Verification of small-scale track deflections should be achievable with Atlantic hurricane aircraft data sets. These data sets could be used to verify whether there is any correspondence between track meanders and changes in vortex structure characteristics. High resolution satellite data could also be used in this context. Improvement in forecasting of short-term track changes is important because this can represent a limitation to the predictability of TC motion.
- (b) The question related to the influence of MCS characteristics on short-term TC motion must be addressed to assess the sensitivity associated with the ability of a middle level vortex to form and be sustained in the TC environment. Although vorticity filamentation has been examined with respect to intensity and structure, a question remains as to the contribution to TC motion.
- (c) Although not explicitly addressed in the rapporteur report, several discussion points were made with regard to the effect of topography on tracks that eventually affects the forecast of landfall.
- (d) The ability of the current observing network and satellite imagery to detect small-scale interactions was questioned in many discussion groups. It was noted that verification of any hypothesis is difficult without supporting data.

5.5 Track prediction techniques

Since IWTC-III there have been significant advances in dynamical track prediction. The development and utilization of the Geophysical Fluid Dynamic Laboratory (GFDL) model has lead the way in dynamical prediction over recent years. Generally, improved track predictions by dynamical models has been attributed to improved horizontal resolution and better physical representations. It has been suggested that further improvements must now come from improved data assimilation and initialization of the TC vortex in the respective model.

Beyond dynamical prediction, advances in track prediction are being made via ensemble forecast techniques and development of track forecast systems such as the systematic and integrated approach to tropical cyclone track forecasting (Carr and Elsberry 1994).

Ensemble forecast techniques are being developed that use ensemble members from the U.S. National Center for Environmental Prediction (NCEP) global model in conjunction with a barotropic model (VICBAR) to generate TC track ensembles. On average, the ensemble mean track was more accurate than any individual track member. Other methods are currently being researched for generation of perturbation fields. On a simpler scale, research has also shown that a simple average of track forecasts emanating from separate global models provides a more accurate track forecast than the individual forecasts on average.

The objective of a TC forecast system is to provide a means by which objective TC forecasts from various sources may be combined and consolidated to maximize subjective interpretation and conceptualization. In the systematic and integrated approach, Carr and Elsberry (1994), define a meteorological knowledge base to assist the forecaster in classifying the current scenario in terms of environmental steering and various TC-environment interactions. The systematic approach is being placed into the context of an expert system that will define model traits for identification of specific characteristics associated with forecast model characteristics.

5.5.1 Issues and discussion

- (a) The potential associated with ensemble forecasting techniques was discussed in the majority of working groups. Perhaps the greatest utility associated with ensemble forecasts is the assessment of a degree of confidence that may be defined by observing the amount of variability in the set of TC track forecasts that comprise the ensemble.

- (b) Forecast systems such as the systematic approach hold great promise as a tool for diagnosing useful information that the forecaster can use. Discussion concentrated on the fact that the forecaster is often presented with too much information and that this information is often contradictory. An efficient forecast system can help to identify useful information.
- (c) It is important to identify when a particular track forecast aid may do well or may do poorly. Research should concentrate on examining this type of variability or instances of variability between different forecast aids. Many discussion groups expressed the sentiment that this was the most immediate way for research to impact forecast operations.
- (d) Improvement in track prediction may best be identified via a forecast demonstration project that can help demonstrate the progress that has been achieved and identify where improvements can be made.

5.6 Summary

The improvement in track prediction accuracy in all basins over the most recent years is evidence that research and increased understanding of various influences on TC track are beginning to have an influence on forecast procedures. A common aspect to all rapporteur reports is the need for observations to validate theoretical and numerical studies of TC motion. It is only after validation that increased knowledge will begin to be manifested through improved forecast accuracy.

The improvement in dynamical track prediction has been a significant advance. The advance can continue through promising new techniques in ensemble forecasting and development of forecast systems that help identify when a forecast aid may do poorly or identify when aids may diverge.

As in most recent years, progress in TC track prediction will continue through a balanced research program that addresses all the characteristics reported on at IWTC-IV.

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CHAPTER 6: TOPIC 4

(Group): Discussed in the Small Group Discussion

(Plenary): Discussed in the Plenary Discussion

6. TROPICAL CYCLONE PREDICTION (by Mitsuru Ueno and Masashi Nagata)

Foreword

- Most end users are only going to evaluate the success or failure of the warning based on a binary yes/no verification.
- The product delivered by the research community must be understood and manageable by the operational forecasters.
- In these days of funding shortfalls and reduced operational and research budgets, it is important to be able to maximize the benefit gained from resources used to provide TC warning services.

6.1 Observational Issues

6.1.1 *Conventional Surface and Upper Air Data*

- The TOGA-TAO buoys provide valuable supplementation of information across the equatorial Pacific area, where there are just a few other observation sites and satellite derived low-level cloud drift winds.
- After the demise of the omega navigational system, a number of developing countries have had to cut back the number of rawinsonde flights from two to one per day as the cost of launching the GPS - equipped sonde has increased by about 50%.
- (Group) Has remote sensing data compensated for the loss of conventional data? The answer to that is generally yes. But the loss of rawinsonde data nevertheless, is a serious problem and further losses could have serious implications. Some areas of the world are more sensitive to this loss of data.
- (Group) A group expressed concern over the reduction in upper-air observations and would like to stress the importance of maintaining and improving the current upper-air sounding network.
- (Group) In relation to Document 10: Establish a single data archive for raw data in each basin. These data would be made readily available for reanalysis of the best tracks and other purposes.
- (Group) A group feels the need for documentation of current observing systems that are used by various countries in forecasting and analysing tropical storms. Also there is a need to know plans of other countries in bringing on board new observing platforms. This documentation should include whether this data is available to other countries and at what cost.
- (Group) A group feels that upper-level commercial aircraft winds (ASDAR) winds are helpful in the data sparse tropics. Their timely collection and dissemination through GPS should be encouraged.

6.1.2 *Aircraft Reconnaissance*

- Manned aircraft have a long history of observations in the Atlantic Basin by penetrating hurricanes. The recent advent of the Gulfstream IV that can cruise at 45,000 feet and

deploy dropwindsondes (DWS) continues this valuable information source for forecasters and researchers.

- Unmanned Aerial Vehicles such as the Autonomous Aerosonde have appeared as a cost-effective alternative means to aerial reconnaissance. Aerosondes are scheduled to operate in a range of field experiments during 1998.

6.1.3 Radar Observations

- In the subsection of radar observations, OSCR (Ocean Surface Current Radar) and OTH (over-the-Horizon) radars which measure upper ocean current and air-sea interactions, were shown to increase research opportunities.
- An application of NEXRAD to TC observations revealed double eye structure in a hurricane.

6.1.4 Satellite Observations

- Once METEOSAT-6 becomes fully operational, the European Space Agency plan to shift METEOSAT-5 to 65 degrees East for research duty in 1998. This is good news for TC monitoring in the South Indian Ocean as the region falls between METEOSAT-6 and GMS-5 views.
- (Plenary) INSAT data may become available.
- (Group) the relocation of METEOSAT-5 to 65 degrees East is only for the duration of a field experiment June 1998 to January 1999. A group expressed interest in exploring the idea that METEOSAT-5 could remain permanently in the new location.
- The higher precision and resolution water vapor sensors combined with optimized data processing strategies has resulted in a major advance in the observation of winds in the upper levels of the troposphere in cloud-free regions.
- (Group) There is a real value for special data such as water vapor derived winds and high resolution sea surface temperature data from new generation satellites. These should be available on a near real-time basis, perhaps via a common Web site.
- (Group) Concerning polar-orbiting satellites, the utilization of recently introduced satellite-observational data such as the scatterometer is encouraged, in addition to conventional data, especially in data sparse areas.
- (Group) Concern was expressed about the implications of the change to the new generation geostationary satellites for National Meteorological Services (NMSS) of many developing countries that largely rely on this source of data for cyclone prediction. Due to limited resources or means available in these countries, assistance from WMO and other sources is necessary to quickly shift to the new access systems.

6.2 Analysis

6.2.1 Conventional Analysis

- Advances in remote sensing and conceptual modelling have helped forecasters to better understand synoptic conditions.

- (Group) A group expressed interest in the development of techniques to get more information from satellite imagery than is available in real time, to all, particularly information which will help in identifying TC center location before an eye is apparent.
- Roadblocks for analysis are 1) lack of ground truth data, 2) incomplete physical understanding and ability to conceptually differentiate between TC and other TC-like disturbances.
- To increase our understanding there are a lot of things to do, such as applying pattern recognition techniques to satellite microwave and multi-spectral imagery. There are also unique challenges in data assimilation and management.

6.2.2 Numerical Analysis

- Very rapid progress has been made in numerical weather prediction in various aspects of TC prediction as a result of considerable improvement in analysis techniques, parameterization of physical processes and considerable increases in model resolution.
- (Plenary) USWRP was introduced, in which variational data assimilation constitutes a major component to improve dynamical TC prediction. In relation to data assimilation aspect, it was proposed to compare total systems including data assimilation.
- (Group) In analysis of low latitude data, do the NWP centers take advantage of all available information in satellite pictures?
- The major roadblock still is lack of observations. This leads to problems in analysing TCs in numerical models.
- (Plenary) SSM/1 data show potential for analysing TCs in regional models.

6.3 Parametric Wind Fields

- Parametric descriptions of the lower tropospheric wind profile in TCs have proven extremely valuable for a variety of applications, such as idealization of structure and behaviour, forecasting, hindcasting, initialization of numerical models, design of offshore and onshore facilities, insurance and so on.
- In spite of various parametric model developments across a wide field, there appears no strongly formed consensus as to the single best representation.
- A comprehensive parametric model is developing the new application areas such as industrial aerodynamics and wind engineering, spectral wave modelling, building fatigue resistance, insurance losses, and so on. Such a comprehensive model should have many application-specific features.
- (Group) A group encouraged further development of parametric models and felt that aircraft data sets could be used to determine the parametric coefficients necessary in those models.
- (Group) There should be further testing of parametric wind models both with regard to their agreement with observed wind fields and their performance when used in numerical model initialization.

6.4 Intensity Prediction Techniques

- Up until the early 1990's, most intensity prediction was based on trends established by observational data.

- There is consensus that the skill of current intensity forecast techniques is far below the desirable level. Scientists are urged to put their efforts into developing models effectively.
- One important issue concerning intensity prediction is that current data bases are not of sufficient accuracy.

6.4.1 *Statistical Methods*

- A baseline statistical intensity forecasting technique based on persistence and climatology should be used at all warning centers.
- (Group) Perhaps a survey could be done of all National Meteorological Services and if no CLIPER-type intensity forecast technique is available, then provide one.

6.4.2 *Statistical-dynamic Method*

- Some other statistical techniques with physical predictors have been used at some warning centers.

6.4.3 *Numerical Prediction Models*

- Although there is a marked improvement in the prediction of track and structure of storms as the horizontal resolution and model physics are improved, most of the models only have modest skill in intensity prediction.
- Regional models are showing good potential for producing TC intensity prediction guidance.
- In conjunction with intensity prediction by numerical models, the mesoscale model intercomparison project (COMPARE) was introduced, in which the explosive development of a super-typhoon is studied.
- (Group) A Chinese expert presented an example of abrupt tropical cyclone intensification in the East China Sea.

6.4.4 *Synoptic, Satellite and Doppler Radar Techniques*

- Despite the success of the Dvorak TC intensity estimation technique, it does have some shortfalls, such as being complicated to apply and a tendency to over-estimate the intensity of a TC after landfall.
- The satellite passive microwave data show some potential for providing a Dvorak-like quantitative intensity estimation techniques.
- (Group) By adding satellite data to the systematic forecasting technique, further improvements should be possible.
- Doppler radars measuring the wind structure of TCs are very useful for very short range intensity prediction.

6.5 *Major Challenges*

- One of the major challenges is to prepare an accurate best track database.
- (Plenary) In connection with best-track database problem, attention was drawn to the diversity of best-tracks for the same storm among centers and the accompanying discrepancies that exist at present.

- (Plenary) TC parameters such as size, maximum wind radius and eye diameter should be included in the best-track data as well as confidence information.
- (Group) Time of peak intensity is another forecast product of intensity and both the Mundell Technique and the MPI (Maximum Potential Intensity) can be used to estimate peak intensity.
- (Group) The necessity of operational forecast guidance for 30 knot and/or 50 knot wind radii was raised.

6.6 Seasonal Prediction Techniques

- Because of the complex nature of the atmosphere/ocean system and the present inability of numerical models to realistically represent all of these complicated nonlinear processes, the hindcasting-based methodology appears to offer a greater likelihood for advances in seasonal predictive skill than do those seasonal forecasts made from initial value numerical modelling.
- When the methodology is applied to seasonal forecasts, one should consider not only SST anomaly but also a variety of global atmosphere-ocean predictors in combination.
- A large historical database is needed to reach a desired level of skill.

6.7 Rainfall Prediction Techniques

- Four methods were introduced for prediction of heavy rainfall in China, associated with typhoons. One of the methods is based on a conceptual model. An example of a synoptic conceptual model for rainfall prediction was shown in the presentation.
- Statistical rainfall forecasting methods use successive regression equations. On the other hand, statistical dynamic prediction schemes can use a neural network system.
- Many operational and research numerical models have been developed in order to predict rainfall.
- In China NMC developed a high-resolution model to predict precipitation and rainfall prediction, and this was verified against four landfalling TCs in August 1997. In CAMS, on the other hand, two nested models were developed and applied to TC rainfall prediction.

6.8 Upgrade to the Forecasters Guide to Tropical Cyclone Forecasting

The rapporteur invited participants' comment on the following three points:

- 1) What changes should be made?
- 2) What format is preferred? The rapporteur proposed to use Web page as a helpful option.
- 3) What structure is most suitable for the guide book?

6.9 Topic overview

- (Group) There exists a large technology gap between RSMCS, or other advanced TC prediction centers, and NMSSs of most developing countries. Therefore, there is a strong need for the formulation of training programs within the regions concerned to provide opportunities for developing countries to adapt to the new technologies.
- (Group) Concern is expressed on the large variety of formats used by cyclone advisory centers in bulletins issued to NMSS, which have difficulty in quickly

interpreting the information contained in these bulletins. Particular problems arise with computer plotting of the information especially the predicted track, which requires a variety of programs to be written and managed. Every effort should therefore be made to address this problem with the ultimate aim to arrive at a common format within the various regions.

- (Plenary) Research community wanted to get real-time access to forecast model output. Although that sounds reasonable, several discussions were made in the context of a problem of multiple sources for advisories. A guideline endorsed by WMO executive council was introduced, in which warning and advisories should be treated separately from forecast guidance.

CHAPTER 7: TOPIC 5

7. TROPICAL CYCLONE IMPACTS by Meng Zhiyong

Introduction

Tropical cyclones have a large economic and societal impact around the world. For example, in 1997 along the Mexican coast Hurricane Pauline resulted in the death of over 400 people, destroyed many farms and businesses, caused hundreds of millions of dollars damage and displaced over 50,000 people (Economist Magazine, 18-24 October 1997 edition). In the United States of America, Hurricane Andrew (1992) caused US\$ 30 billion in losses, and the United States experiences more than US\$ 5 billion in losses annually (Pielke and Landsea, 1998). The Western Pacific basin has about one-third of global tropical cyclones and countries along its western coast experience severe disasters. Statistics show about 5 tropical cyclones make landfall in China every year. In 1975, Typhoon Nina caused two huge reservoirs to collapse at almost the same time, claimed 100,000 lives and RMB 100 billion of economic losses. In the Indian sub-region, cyclones can cause extensive damage to property and result in human casualties including fatalities especially in India and Bangladesh. In 1991, a tropical storm struck Bangladesh from Bay of Bengal. Owing to severe storm surge in addition to strong winds and torrential rain, 139,000 people were killed. In Australia, tropical cyclones are one of the most economically significant natural disasters responsible for the highest insurance pay-outs. The Insurance Council of Australia indicated that the average cost of a tropical cyclone in terms of insurance pay-outs was about 75 million Australian dollars (A\$) over the 20-year period from 1970 to 1989. The average annual total costs could be A\$ 300 million (Joy 1991).

The reports presented for Topic 5 Chapter 7 represent a starting point for the further development and refinement of knowledge on tropical cyclone impacts. Section 7.1 overviews the methodologies of economics and damage normalization. A need to set up a global database on tropical cyclone impacts is put forward. Section 7.2 presents social disruptions caused by tropical cyclones, methodological issues in social impact assessment and policy response especially to the improved forecast. Section 7.3 presents an overview of the warning process from the U.S. and China. Some issues concerning warning response are also covered. Section 7.4 presents resource information issues associated with TC information obtained over the Internet or via other media.

7.1 Economic Impacts

7.1.1 *Economic classification of impacts from tropical cvclones.*

Economic impacts from tropical cyclones can be classified into the following three aspects:

- negative and positive impacts:

When we talk about tropical cyclone impacts, the negative impacts are usually the focus. The positive impacts should not neglected because rainfall from TCs acts as the main water sources in some regions.

- direct and indirect impacts:
- tangible and intangible impacts.

To assess the degree of a disaster, the economic status of the local government should be considered. It is often the case that impacts in less developed or smaller countries can have a proportionally much greater impact on a regional or national economy. Damage that may be

considered as small to a large developed country may be devastating to some small island nations where the economics are based largely on tourism and/or agriculture.

7.1.2 Trends and Methodology

In the three kinds of economic impacts mentioned in 5.1.1, most recent work has involved the direct economic impacts of TCs. Based on the direct economic impact data, trends of impact can be obtained to give some indication of future impact and what should be done in disaster mitigation.

Changes in tropical cyclone impacts result from changes in storm frequency and also societal changes. So, to make comparisons over time and between regions, it is important for any assessment of losses to incorporate normalization techniques.

Consider the case of the United States where losses have been quickly increasing within the last two decades, even after considering inflation. To best capture the year-to-year variability in tropical cyclone damage, consideration must be given toward two additional factors, coastal population changes and changes in wealth. With this normalization, the trend of increasing damage amounts is replaced by multi-decadal variation with less damage in 1970s and 1980s than in previous decades. So, it is the societal change instead of meteorological elements that contributes to the increasing trend of damage or losses. Climate changes may have played a negative role with a decrease in the frequency of intense TCs in the U.S. in recent decades (Landsea et al. 1996).

Other countries are encouraged to perform similar investigations to improve our knowledge on this aspect. This effort will play a very important role in future decision making.

7.1.3 Global Disaster Data Base

There is a need to develop a global damage database (i.e., damage statistics from the start of the century) to be used to make better assessments of the forecast/warnings issued. It would also help to mitigate future losses. Data collecting and processing may involve full-time researchers and experts from other disciplines such as economists.

This database should include not only data on negative impacts but also on positive impacts.

Another important point is these data have yet to be systematically collected and assessed in a common format to make it possible to do comparisons between different times and regions. It was discussed that WMO has a format for reporting such information, though not everyone is familiar with it.

The final key point concerning a disaster database is the validation, or the accuracy of disaster data. Sometimes, subjective reassessments of losses may be included. The data should be as accurate as possible.

7.1.4 Literature Review Concerning Tropical Cyclone Impacts

There is a need to set up a working group of experts to review the international and national literature on economic and social impacts of tropical cyclones worldwide. The terms of references may include the use of historical impact data to predict future economic and social impacts, and the assessment of the ability of tropical cyclone warning and information services to reduce damage. This group should produce a final report to submit to the next IWTC.

It is up to WMO to design the structure of the group and nominate the members from different regions of the world.

7.2 Societal Impacts

7.2.1 Social Disruption

Societal impact can be more severe than economic impact. The disruption caused by tropical cyclones is mainly due to strong winds, heavy rainfall or storm surge. In 1988, Typhoon Bill hit Zhejiang province in China. Gale force winds lasted about 5.5 hours, which caused power failure over the whole city. Considerable damage was done to the beautiful West Lake scenery in this very short period (Hangzhou).

7.2.2 Database

Compared to economic impacts, it is more difficult to obtain societal impact data. Considerable effort is needed to collect and process this kind of disaster data. Multiple order (i.e., indirect and intangible impacts) impacts need to be considered in time and space.

7.2.3 Methodological Issues in Assessment of Societal Impacts

- Attribution of causal factors underlying the impact needs to be investigated, such as societal changes and past policies.
- Measurement of societal impact. Qualification is urged to make trend analysis possible.
- There is a need to find a way to integrate the benefits of tropical cyclone impacts with losses.
- Some techniques should be developed to best compare impacts at different times and places.

7.2.4 Policy Response

The usage of impact information in the policy process needs to be studied to prioritize resources for response.

Considering long term disaster mitigation, vulnerability assessment should be paid more attention to enhance mitigation efforts. Decision-makers should have a good idea on what would happen if the building construction code is not upheld and if coastal management procedures do not fit vulnerability criteria.

Another focal point is the use and value of improved forecasts. An improved forecast should be accompanied by efficient warning and social response. Also, an improved forecast should probably result in the decrease of the warning area and as a result the decrease of the preparedness cost. For small islands, it will reduce false alarms. This will encourage local governments to give more financial support to both research and operational units to attain further improvement. Consequently, there is need to develop techniques to measure the avoidable cost from a socio economic perspective.

7.3 Warning Process

7.3.1 Forecast and Warning Practices

- *The U.S.National Hurricane Center (NHC)*

The hurricane specialists at the National Hurricane Center (NHC) issue track, intensity and surface wind structure forecasts that extend up to 72 hours. The information is released every six hours and includes forecast and public advisories, a tropical cyclone discussion and strike probabilities.

The importance of a detailed analysis of the initial wind field is emphasized. The Dvorak technique needs to be improved to get a better recognition of short-term changes in the cloud

pattern from satellite imagery. Next to track forecasting, intensity forecasting techniques/models need to be improved.

- *China National Meteorological Center*

China National Meteorological Center issues timely and frequent tropical cyclone warnings with update information broadcast by its TV network. Those warning programs show the public informative data including weather records and satellite imagery. The warning picture can show the public the real shape and size of the TC, its eye position, the location of strong wind and heavy rain, its position relative to environmental weather systems and the tendency of the TC movement, etc. Warnings are also issued by other means including radio and fax.

7.3.2 Warning Response

- **Forecast Accuracy and Reliability.** To attain effective warning response, the first step is to increase forecast accuracy and reliability. It is important to increase the confidence of the public on the forecast and warnings. In this aspect, seasonal tropical cyclone forecasts should be given more attention.
- **Communication Efficiency.** Another important point is the efficiency of communication. Up to now, radio has always been the most effective way to issue warnings. The usage of radio communication should be optimized.
- **Format.** The format of warnings should adopt descriptive terminology and graphics to make it easy to be understood.
- **Easier Evacuation.** Evacuation processes can be made easier if it is accompanied by good sheltering policy, e.g., shelters being used and maintained as schools or community centers in non-emergency situations but capable of being activated in short-time for sheltering purposes.
- **Public Awareness towards Tropical Cyclone Impact.** Special programs should be encouraged to enhance public awareness about tropical cyclone events to the general public, decision makers, media.
- **A Chinese Case in Warning Response.** There are three types of warnings in China including tropical cyclone warning (typhoon may land on China in 72 hours); typhoon warning (typhoon may land in 48 hours), urgent warning (typhoon may land in 24 hours). Efficiency of the warning response depends on good cooperation between meteorological service, decision-making bodies and the threatened public. In 1986 rather good cooperation was carried out when Peggy hit Guangdong Province. No fisherman were killed, 35 reservoirs within the affected area survived the storm. It was estimated that an economic loss of more than 1000 million Yuan were avoided in Guangdong Province alone.

7.4 Information Issues

7.4.1 Availability of Advisories

Web sites are and will be a very useful channel for future information exchange. As operational advisories become available on the Internet, it is becoming increasingly easy for people to access warnings from agencies and organizations other than those that have official responsibility for the area. The potential for conflicting information to reach the community then becomes quite significant.

This confusion in differences among warning centers comes from several sources such as the difference in wind averaging-times, analysis and forecast disagreements between warning centers and a difference in TC status between warning centers caused by either or both of the above points.

The possible solutions to ease the confusion include:

- Setting a common wind standard
- Better coordination and data sharing between warning centers.
- WMO designated TCP RSMC for each region to be accepted source of guidance information, and the international media is also encouraged to use the RSMCs for their source.
- Better education of the public to the uncertainties of TC analysis and forecasting and of the forecast process. Any advisory should identify its source warning center.
- A need to clarify which office or organization is responsible for issuing "official advisories" to a local area. It is suggested that the National Weather Service be in charge of "official tropical cyclone advises and warnings".

7.4.2 Archiving of Physical Science Data

- *Best Track Data*

It is suggested that other data like TC size be added to "Best Track" data.

Global "best track" databases are now easily accessible for the Atlantic and northeast Pacific basins, the data is available via Web at: <<http://www.nhc.noaa.gov/pasthur.html>>. For some of the remaining basins, the data are available via a CD-ROM.

With the improvement of analysis techniques, the "Best Track" database may need to be reanalyzed.

- *Observations of Tropical Cyclones*

It is suggested that a database be set up on a global basis. WMO should consider addressing the reporting of peak gusts and time of minimum sea-level pressure for tropical cyclones in the synoptic code. Tropical cyclone warning centers should be encouraged to include in their archive data sets the wind radii and fix (synoptic, satellite, radar, and aircraft) information.

7.4.3 Communication Issues Within Tropical Cyclone Community

A tropical storms mailing list has been set up to foster communication among the research and forecasting community. It is recommended that an effort be made to encourage more forecasters and more individuals from developing countries to participate in these internet discussions.

7.4.4 Education issues

One obvious resource of which more advantage should be taken is the Internet. Providing freely accessible material on tropical cyclone via the Web can be a benefit to both forecasters and the general public. For example, it was suggested that the FAQ (Hurricanes, Typhoons and Tropical cyclones frequently asked questions) file maintained by Chris Landsea <<http://www.anomi.noaa.gov/lhrdltcfaq/tcfaqHED.html>> be translated into languages other than English.

7.5 References:

- Joy (1991)
- Landsea et al. (1996)

- Piece and Landsea (1998)

SUMMARY OF FORECASTERS' FORUM

by

Ian Shepherd

Discussion Points/Issues

1. IWTC-III Recommendations

The meeting commenced with a summary of recommendations from the IWTC-III meeting relevant to forecasters. Issues raised in those recommendations were the same as in the current meeting. However, some progress has been made in the past four years. Improved communications, coordination and information exchange; education and training; access to research materials and archival of data in National Weather Services were some of the important ongoing issues.

2. Improvement in TC Forecast Errors

National Hurricane Center, Miami, Florida, Atlantic TC track errors have been reduced at all forecast times during the past 10-20 years, with a significant improvement in the past 3-4 years. The recent improvements were attributed in part to improvements in global spectral models, the introduction of the GFDL model and implementation of automated display systems in the forecasting office. Similar improvements have occurred in other forecasting centers with access to high technology systems, and a further reduction in track forecast errors is expected. However, an improvement in TC intensity and structure forecasts is now needed. It was recommended that all warning centers maintain a record of warning verification statistics in order to monitor their performance.

3. Warning Area and Lead Time

An increase in the average area warned during the past two decades along the U.S. coast, despite improvements in track forecasts was attributed to an increase in the lead time required by emergency managers, together with an increase in community vulnerability as a result of rapid coastal development.

4. Long Period Forecasts

There is an increasing demand for longer period TC forecasts from the media and public, as routine weather forecast periods for coastal cities extends to five days. However, TC track errors for the GFDL model almost double from 72 hours to 120 hours, indicating the effective limit of useful TC forecasts.

5. Observations

New remote sensing techniques (SSM/1, scatterometers, radar altimeter) together with targeted observations using GPS dropsondes and unmanned aircraft are expected to improve short-term forecasts, as well as improve TC position and structure estimates used in numerical model initialization.

6. Numerical Prediction Techniques

Statistical and statistical-dynamic models can add skill to numerical model output through the inclusion of factors such as climate trends and regional effects. These techniques are particularly useful in situations when models do not perform well, and in these cases, an

examination of the reasons for each forecast failure could yield useful information about model performance. In particular, pattern typing techniques have potential to improve the forecaster's interpretation of a divergent ensemble of model forecasts in conjunction with an understanding of model physics and limitations.

7. The Systematic Approach

The use of the Systematic Approach to TC track forecasting has contributed to improved track forecasts in the northwest Pacific and has recently been extended to the Australian region. The application of this approach to track forecasting is encouraged in all cyclone warning centers.

8. Communications

Many developing countries have limited access to numerical prediction models due to slow GTS links. A specific recommendation was made to upgrade the Hanoi-Beijing GTS link.

9. Information and Technology Transfer

Many warning centers also have limited access to information including TC databases, forecasting techniques, research papers and to real-time satellite data essential to TC forecasting and research. Sources of information such as RSMC seasonal summaries, annual reports, WMO operational plans and regional typhoon committee reports were described to meeting participants and the availability of numerical model grid point data from various RSMCs via GTS was highlighted. A suggestion was made for unwanted journals and textbooks to be donated to warning centers in developing countries. The tropical storms e-mail bulletin board was described, which has been a useful medium for information exchange between forecasters and researchers in recent years. A recommendation was made to establish a TC forecaster Web site parallel to the proposed Forecaster's Guide site on which operational studies, forecaster rules and other relevant material could be posted.

10. Future IWTC Meetings

The meeting was assured that the IWTC series of workshops was regarded as a high priority in the WMO TC program, and that participants could look forward to a continuing series of meetings.

List of Topic Chairmen and Rapporteurs

Topic 1 - Tropical Cyclone Landfalling Cyclones (Chair: F. Marks (USA))

- 1.1 The USWRP Landfalling Tropical Cyclone Research Programme (F. Marks (USA))
- 1.2 Wind transients, Vertical Structure and Gust Factors in Tropical Cyclones (P. Black (USA))
- 1.3 Ocean Processes excited by tropical cyclones (Shay (USA))
- 1.4 Modification of track at Landfall (E. Rappaport (USA))
- 1.5 Rainfall (D. Renqing (China))
- 1.6 Decay after Landfall (F. Marks (USA)) and (L. Chen (China))

Topic 2 - Tropical cyclone intensity and structure (Chair: G. Holland (Australia))

- 2.1 Air-sea Interaction (J. Lighthill (UK))
- 2.2 Environmental Interaction (J. Molinari (USA))
- 2.3 Tropical cyclone maximum intensity theory (K. Emanuel (USA))
- 2.4 Tropical cyclone formation (W. Frank (USA))
- 2.5 Small and Mesoscale Interactions (E. Ritchie (USA))

Topic 3 - Tropical cyclone motion (Chair: R. Elsberry (USA)) and Co-chair (H. Yan (China))

- 3.1 Environmental Interaction (J.C.L. Chan)
- 3.2 Baroclinic Processes (B. Wang (USA))
- 3.3 Barotropic processes (R. Smith (Germany))
- 3.4 Small scale interactions (M. Lander (USA))

Topic 4 - Tropical Cyclone Prediction (Chair M. Andrews (USA))

- 4.1 Observational Issues (S. Ready (New Zealand))
- 4.2 Analysis (F. Wells (USA))
- 4.3 Parametric Wind Fields (B. Harper (Australia))

- 4.4 Track Prediction Techniques (L. Carr III (USA))
- 4.5 Intensity Prediction techniques (C. Guard (USA))
- 4.6 Seasonal Prediction Techniques (W. Gray (USA))
- 4.7 Rainfall Prediction Techniques (X. Xiangde (China))
- 4.8 Upgrade to the Global Guide to Tropical Cyclone Forecasting (G. Holland (Australia))

Topic 5 *Tropical cyclone Impacts (Chair R. Pielke Jr (USA) and Co-chair K. McGuffie (Australia))*

- 5.1 Economic Impacts (K. McGuffie (Australia))
- 5.2 Societal Impacts (R. Pielke Jr (USA))
- 5.3 The warning process (L. Avila (USA))
- 5.4 Information Issues (C. Landsea (USA))

List of Topic Rapporteurs responsible for final workshop report

| | |
|---------|---|
| Topic 1 | Landfalling Cyclones - K. McGuffie (Australia) |
| Topic 2 | Tropical Cyclone Intensity and Structure - C. Landsea (USA) |
| Topic 3 | Tropical Cyclone Motion - P. Harr (USA) |
| Topic 4 | Tropical Cyclone Prediction - M. Ueno and N. Nagata (Japan) |
| Topic 5 | Tropical Cyclone Impacts - Z. Meng (China) |

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